B-16

OPERATING INSTRUCTIONS
FOR
# TYPE 716-B
# CAPACITANCE BRIDGE
FORM 455-C

GENERAL RADIO COMPANY
CAMBRIDGE 39, MASSACHUSETTS

# OPERATING INSTRUCTIONS
# FOR
# TYPE 716-B
# CAPACITANCE BRIDGE

Form 455-C

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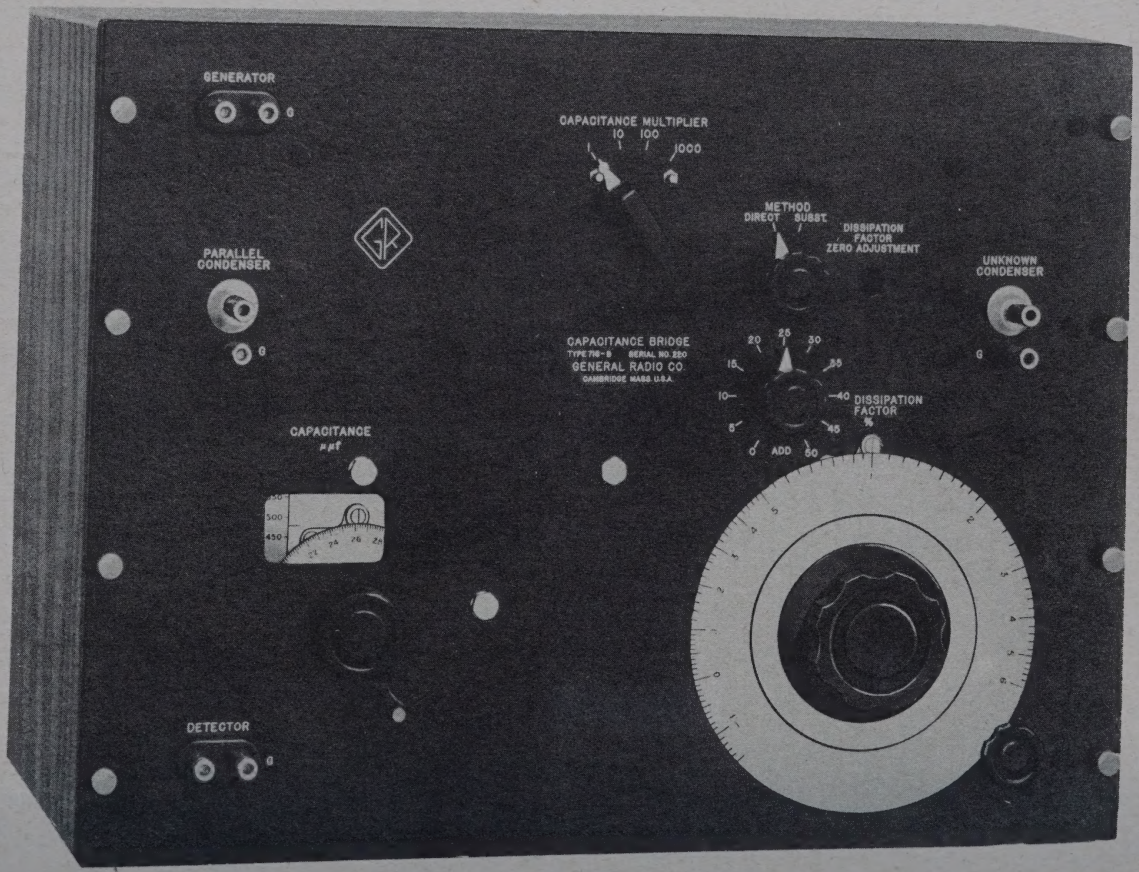

GENERATOR
CAPACITANCE MULTIPLIER
10
100
1
1000
METHOD
DIRECT
SUBST.
DISSIPATION FACTOR ZERO ADJUSTMENT
PARALLEL CONDENSER
UNKNOWN CONDENSER
CAPACITANCE BRIDGE
TYPE 716-B SERIAL NO. 220
GENERAL RADIO CO
CAMBRIDGE MASS. U.S.A.
20
25
30
15
35
10
40
DISSIPATION FACTOR
%
5
45
0
ADD
50
CAPACITANCE
μμf
500
450
DETECTOR

# OPERATING INSTRUCTIONS
# FOR
# TYPE 716-B
# CAPACITANCE BRIDGE

## PART 1

### DESCRIPTION

The Type 716-B Capacitance Bridge is a Schering bridge which is direct reading in capacitance at all audio frequencies and in dissipation factor at at frequency of 1 kc. The resistance balance is made by means of a variable condenser connected across one of the ratio arms, as shown in Figure 1. Hence its readings in dissipation factor are proportional to frequency.

The bridge may also be used for all types of substitution measurements by the addition of a fixed or variable balancing condenser. The direct-reading scales greatly simplify the necessary calculations for capacitance and dissipation factor.

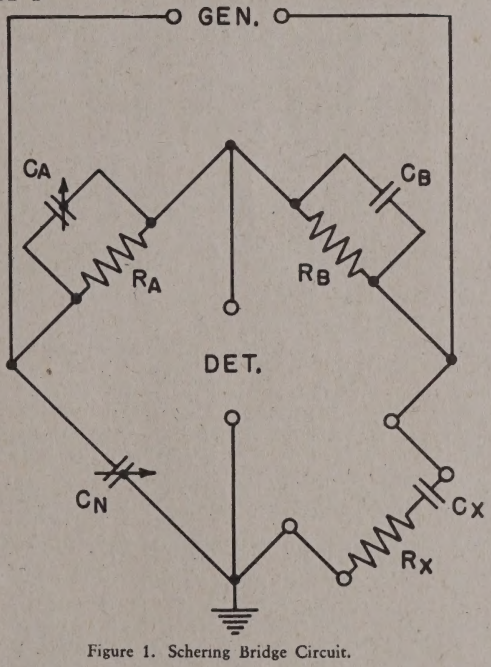


Figure 1. Schering Bridge Circuit.

### RANGE AND ACCURACY

The ranges of the bridge in both capacitance and dissipation factor at a frequency of 1 kc are given in Table I for both direct-reading and substitution methods. Minimum values are set by the direct-reading limits of the scales or by 1/5 of the smallest division. The maximum errors occuring in the final result are also given in Table I. All the values given are necessarily condensed and are explained in full in Part 3 under the heading *Accuracy*.

TABLE I

| | | Range | | Error | |
|---|---|---|---|---|---|
| Method | Quantity | Minimum | Maximum | Actual | Fractional |
| Direct Reading | C | 100 $\mu\mu$f | 1 $\mu$f | 2 $\mu\mu$f $\times M$ | 0.2% |
| | D | 0.00002 | 0.56 | 0.0005 | 2 % |
| Substitution | C | 0.04 $\mu\mu$f | 1000 $\mu\mu$f | 2 $\mu\mu$f | 0.2% |
| | D | $0.00002 \times \frac{C'}{C_x}$ | $0.56 \times \frac{C'}{C_x}$ | $0.00005 \times \frac{C'}{C_x}$ | 2 % |

Dissipation factor, $D = \frac{R}{X} = R\omega C$, is numerically equal to power factor within 2% for all values less than 0.2.

$M$ = multiplier setting. $C'$ = total capacitance in arm. $C_x$ = unknown capacitance.

# PART 2—INSTALLATION

## ACCESSORIES SUPPLIED

One Type 274-NC Shielded Conductor, one Type 274-NE Shielded Conductor, and one Type 274-M Plug are supplied with each Type 716-B Capacitance Bridge for connecting to the generator and detector.

## ACCESSORIES REQUIRED

A generator and detector are required to supply power to the bridge and detect the balance points. These instruments may be operated from batteries or from the a-c supply. Suitable combinations* are as follows:

**Battery Operation**

Type 813-A Audio Oscillator
Type 723 Vacuum-Tube Fork
Type 814-A Amplifier
Type 760-A Sound Analyzer

**A-C Operation**

Type 608-A Oscillator
Type 713-B Beat-Frequency Oscillator
Type 913-A Beat-Frequency Oscillator
Type 714-A Amplifier
Type 736-A Wave Analyzer
Type 707-A Cathode-Ray Null Detector

The actual detector may be a pair of head telephones (Western Electric 1002-C or their equivalent in sensitivity and resistance) or a high-resistance rectifier or vacuum-tube voltmeter. The Type 483-F Output Meter or the Type 726-A Vacuum-Tube Voltmeter are suitable. The sensitivity of the head telephones around 1 kc is about 40 db greater than that of either of the voltmeters.

Selectivity, which is inherent in head telephones, must be provided for most of the other detectors by tuned circuits or band-pass filters. The Type 814-P Tuned Circuits and Type 830 Wave Filters are suitable. The Type 760-A Sound Analyzer, Type 736-A Wave Analyzer and Type 707-A Null Detector are in themselves highly selective.

*See the General Radio Catalog for data.

## CONNECTIONS

Connect the generator and detector to the bridge by means of the shielded conductors with the shield side of the conductors connected to the terminals marked G on *all* instruments. Connect one of these ground terminals to a good ground. The Type 274-NE, which has shielded terminals, should be used to connect the bridge to the detector. The bridge may be operated with its panel either horizontal or vertical.

The bridge will, of course, *not* balance until a capacitance greater than 50 $\mu\mu$f is connected across the UNKNOWN CONDENSER terminals.

# PART 3—MEASUREMENTS

## A. DIRECT READING METHOD

### Procedure

Connect the condenser to be measured to the UNKNOWN CONDENSER terminals with its shield or ground side connected to the lower terminal marked G. Use as short leads as possible.

Set the METHOD switch at DIRECT. Set the DISSIPATION FACTOR switch at 0, unless it is known that the dissipation factor of the unknown condenser is greater than 0.06 (6%). Set the CAPACITANCE MULTIPLIER switch in the proper position if the capacitance of the unknown condenser is known approximately, and in any case at that position which shows the least unbalance of the bridge. The gain of the amplifier should be turned down at first so that overloading will not occur.

Adjust the CAPACITANCE and DISSIPATION FACTOR dials alternately until a sharp balance is obtained on both, readjusting the CAPACITANCE MULTIPLIER and DISSIPATION FACTOR switches if necessary. The capacitance balance usually must be made more closely than it can be read in order to obtain a dissipation factor balance to a tenth division on the dial.

The series capacitance of the unknown condenser expressed in $\mu\mu$f is the reading of the

CAPACITANCE drum and dial multiplied by the setting of the CAPACITANCE MULTIPLIER.

$$C_X = MC \qquad (1)$$

where $M$ is the multiplier setting.

One turn of the dial corresponds to 50 $\mu\mu$f. The last two figures of the capacitance reading to the left of the decimal point are either the actual dial reading or that reading increased by 50, depending on whether the reading of the drum is an even 100 or ends in 50. The dial and drum are direct reading only between 100 and 1100 $\mu\mu$f.

The dissipation factor of the unknown condenser expressed in percent is the sum of the readings of the DISSIPATION FACTOR switch and dial.

$$D_X = D \qquad (2)$$

The series resistance of the unknown condenser, its parallel capacitance and its parallel resistance can be calculated from the expressions

$$R_X = \frac{D_X}{\omega C_X}$$

$$C_{XP} = \frac{C_X}{1 + D_X^2} \qquad (3)^*$$

$$R_{XP} = \frac{1 + D_X^2}{D_X \omega C_X}$$

Hence

$$R_X = \frac{D}{\omega MC}$$

$$C_{XP} = \frac{MC}{1 + D^2} \qquad (4)$$

$$R_{XP} = \frac{1 + D^2}{\omega DMC}$$

The fixed capacitances across the ratio arms $A$ and $B$, represented in Figure 1 as $C_B$ and the zero capacitance of $C_A$ (see Part 4, Section B), produce errors in both the capacitance and dissipation factor readings of the bridge, when the dissipation factor of the unknown condenser is large. Approximate expressions applying to the unknown condenser are

$$C_X = \frac{MC}{1 + DD_0}$$

$$D_X = \frac{D}{1 + DD_0}$$

$$R_X = \frac{D}{\omega MC} \qquad (5)$$

$$C_{XP} = \frac{MC}{1 + D^2} \frac{1}{1 + DD_0}$$

$$R_{XP} = \frac{1 + D^2}{\omega DMC}(1 + 2DD_0)$$

where $D_0$ is the dissipation factor corresponding to the fixed capacitances across the ratio arms and has the value 0.034 (3.4%) within 5%, when the METHOD switch is set at DIRECT. Both bridge readings are high by the factor $1 + DD_0$. In order to realize the maximum accuracy of the bridge, Equations (5) should be used for capacitance when $D > 0.01$ (1%), for parallel resistance when $D > 0.05$ (5%) and for dissipation factor when $D > 0.1$ (10%). The expression for series resistance is not subject to this kind of error. Values of the fractional correction $DD_0$ for different values of $D$ are given in Table II.

TABLE II

Fractional Correction

| $D$ % | $-DD_0$ % | $D$ % | $-DD_0$ % |
|---|---|---|---|
| 5 | — .17 | 35 | —1.19 |
| 10 | — .34 | 40 | —1.36 |
| 15 | — .51 | 45 | —1.53 |
| 20 | — .68 | 50 | —1.70 |
| 25 | — .85 | 55 | —1.87 |
| 30 | —1.02 | | |

### Accuracy

The accuracy of the capacitance reading is 0.2% or 2 $\mu\mu$f times the reading of the CAPACITANCE MULTIPLIER, whichever is the greater, over the range 100 $\mu\mu$f to 1.1 $\mu$f, provided the dissipation factor reading is less than 0.01 (1%). This accuracy can be maintained

*All formulae given in this booklet, except Equations (22) and (23) are consistent when the practical electromagnetic units are used, ohm, henry, farad, cycle, radian, with dissipation factor expressed as a ratio. Whenever these quantities appear as ratios, the units in which the bridge reads directly, micromicrofarads and percent dissipation factor may be used. When these units are used in Equations (1), (2), (6), (7), (11), (12), (19), (20) and (21), the results are in the same units.

for greater dissipation factor readings by using Equations (5).

The fractional accuracy, therefore, varies from 0.2% for full-scale setting of the CAPACITANCE dial to 2% for a setting of 100 $\mu\mu$f for each of the four settings of the MULTIPLIER.

The CAPACITANCE dial itself is direct reading to 1 $\mu\mu$f or 0.1%. The other 1 $\mu\mu$f error is the stray capacitance across the UNKNOWN CONDENSER terminals. This is almost wholly the capacitance between the external post and the other grounded post and panel, because the lead inside the isolantite bushing is shielded. The other 0.1% error comes from errors in the ratio arms which are adjusted to 0.1%, and from leakage impedances in the shielded transformer. It is probable that the fractional error for a setting of the CAPACITANCE dial of 100 $\mu\mu$f is not greater than 1% for all settings of the MULTIPLIER except 1.

The leads used to connect the unknown condenser to the terminals will add some capacitance. This introduces a positive error which must be subtracted from the bridge reading. The capacitance of leads of No. 16 bare wire with ¾-inch spacing is about 0.3 $\mu\mu$f per inch. Most of this capacitance is associated with the high lead, which therefore should *not* be insulated. It will amount to 1.2 $\mu\mu$f for the shortest possible leads used when the panel of the unknown condenser is flush with and touching the panel of the bridge. This capacitance may be measured as described in Section B.

The accuracy of the dissipation factor readings is 0.0005 (0.05%) or 2%, whichever is the greater, provided the dissipation factor reading is less than 0.1 (10%). This accuraccy can be maintained for greater dissipation factor readings by using Equation (5). It is difficult to state exactly how the error varies over the dissipation factor range from zero to 6% because the scale of the DISSIPATION FACTOR dial is semi-logarithmic. The mica condensers controlled by the DISSIPATION FACTOR switch are so adjusted that the accuracy of the switch settings is 1%.

The dissipation factor of the standard condenser varies from 0.004% at 1000 $\mu\mu$f to 0.04% at 100 $\mu\mu$f. The effect of this is partially neutralized by errors arising from leakage impedances in the shielded transformer. One of the capacitances between shields in this transformer is connected across the *A* arm as shown in Figure 6, and has an appreciable temperature coefficient of capacitance. It is probable that, when the DISSIPATION FACTOR ZERO ADJUSTMENT is made, as suggested in Part 5, Section B, the error in the dissipation factor readings will not exceed 0.0002 (0.02%) or 2% of the sum of the switch and dial readings.

## B. SUBSTITUTION METHOD

### Procedure

Many of the errors inherent in direct readings across the bridge may be eliminated by using the substitution method in which the standard air condenser is always kept in circuit and the unknown condenser is substituted for part of it. The capacitance range of this method is that of the standard condenser, 1000 $\mu\mu$f.

Set the METHOD switch at SUBSTitution and the CAPACITANCE MULTIPLIER switch at 1. Connect a balancing condenser to the UNKNOWN CONDENSER terminals. Connect the low terminal of the unknown condenser to the PARALLEL CONDENSER terminal marked G, as shown in Figure 2, leaving the high lead separated from the terminal of the unknown condenser by about ¼ inch. Make this lead a stiff bare wire of small diameter.* Balance the bridge for capacitance and dissipation factor as described in Section A. This balancing condenser must be at least 100 $\mu\mu$f larger than the unknown condenser and may be either fixed or variable. Type 505 Condensers, Type 509 Standard Condensers, Type 539 Variable Air Condensers and Type 722 Precision Condensers are suitable.† With the METHOD switch set at SUBSTitution the condensers controlled by the DISSIPATION FACTOR switch and dial are connected across the *B* arm.

Connect the unknown condenser on its high terminal and rebalance the bridge. The new reading for capacitance will be less than, and the new reading for dissipation factor will be greater than, the initial readings.

The capacitance and dissipation factor of the unknown condenser can be calculated from the changes in readings of the CAPACITANCE and DISSIPATION FACTOR dials.

$$C_x = \Delta C$$
$$D_x = \frac{C'}{\Delta C}\,\Delta D \qquad (6)$$

*R. F. Field, "Connection Errors in Capacitance Measurements," General Radio *Experimenter*, January, 1938.

†See the General Radio Catalog for data.

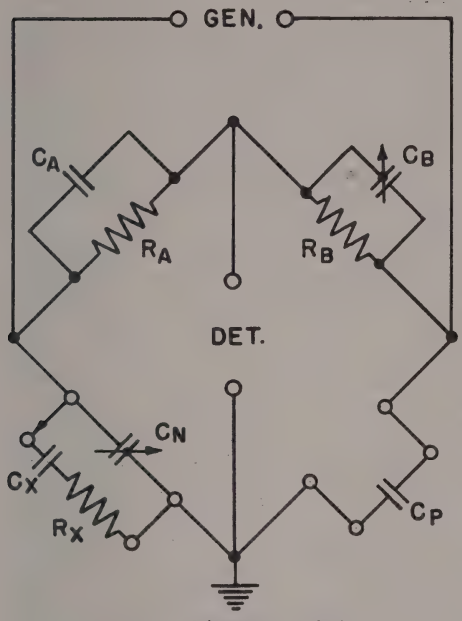



Figure 2. Substitution Method.

where initial readings are designated by primes and Δ stands for "change in".

$$\begin{aligned} \Delta C &= C' - C \\ \Delta D &= D - D' \end{aligned} \qquad (7)$$

The initial capacitance $C'$ appearing in the dissipation factor equation should include the capacitance of the leads to the unknown condenser. This capacitance may be found by making a third bridge balance in which the leads are removed. The change in reading of the CAPACITANCE dial from its initial reading is the lead capacitance. The losses in the standard condenser do not appear in the expression for dissipation factor because these losses are constant and are in circuit at all times.

When the balancing condenser is variable, the CAPACITANCE dial may be set exactly at an even hundred $\mu\mu$f. The change in capacitance $\Delta C$ may then be read directly by reading the scale backward.

The series resistance, parallel capacitance and parallel resistance of the unknown condenser can be calculated by means of Equations (3) or directly from the expressions

$$R_X = \frac{C'\Delta D}{\omega(\Delta C)^2}$$

$$C_{XP} = \frac{\Delta C}{1 + (\Delta D)^2\left(\frac{C'}{\Delta C}\right)^2} \qquad (8)$$

$$R_{XP} = \frac{1 + (\Delta D)^2\left(\frac{C'}{\Delta C}\right)^2}{\omega C'\Delta D}$$

The calibration of the DISSIPATION FACTOR dial is extended below zero to −0.15% so that the bridge can be balanced initially even when the dissipation factor of the balancing condenser is greater than that of the standard condenser in the bridge. Advantage may also be taken of this negative calibration in allowing substitution measurements to be made with the METHOD switch set at DIRECT. For this connection the dissipation factor reading with the unknown connected will be less than the corresponding initial reading.

When the dissipation factor of the unknown condenser is greater than 0.1 (10%) and the dissipation factor setting with the unknown connected is entirely contained on the DISSIPATION FACTOR dial, Equations (6) and (8) require certain correction terms and become:

$$\begin{aligned} C_X &= \Delta C\,\frac{1 + (\Delta D)^2\left(\frac{C}{\Delta C}\right)^2}{1 - (\Delta D)^2\frac{C}{\Delta C}} \\ D_X &= \frac{C'}{\Delta C}\,\frac{\Delta D}{1 - (\Delta D)^2\frac{C}{\Delta C}} \\ R_X &= \frac{C'}{\omega(\Delta C)^2}\,\frac{\Delta D}{1 + (\Delta D)^2\left(\frac{C}{\Delta C}\right)^2} \end{aligned} \qquad (9)$$

$$C_{XP} = \Delta C\,\frac{1 - (\Delta D)^2\frac{C}{\Delta C}}{1 + (\Delta D)^2}$$

$$R_{XP} = \frac{1 + (\Delta D)^2}{\omega C'\Delta D}$$

When the dissipation factor of the unknown condenser is very large, (a value of 1, or 100%, is a good dividing line) the zero capacitance of the ratio arm containing the DISSIPATION FACTOR condensers produces additional er-

rors, and the following expressions should be used:

$$C_x = \Delta C \frac{1 + \left(D' - \Delta D \frac{C}{\Delta C}\right)^2}{1 + D\left(D' - \Delta D \frac{C}{\Delta C}\right)}$$

$$D_x = \frac{C'}{\Delta C} \frac{\Delta D}{1 + D\left(D' - \Delta D \frac{C}{\Delta C}\right)} \qquad (10)$$

$$R_x = \frac{C'}{\omega(\Delta C)^2} \frac{\Delta D}{1 + \left(D' - \Delta D \frac{C}{\Delta C}\right)^2}$$

$$C_{xp} = \Delta C \frac{1 + D\left(D' - \Delta D \frac{C}{\Delta C}\right)}{1 + D^2}$$

$$R_{xp} = \frac{1 + D^2}{\omega C' \Delta D}$$

where the dissipation factor readings $D$ and $D'$ must be increased by $D_0 = 0.042$ (4.2%), the dissipation factor corresponding to the fixed capacitances across the ratio arms when the METHOD switch is set at SUBSTitution. Equations (10) should be used when $D'$ or 0.042 is not negligible compared to $\Delta D \frac{C}{\Delta C}$

### Accuracy

The accuracy of the calculated capacitance is 2 $\mu\mu$f or 0.2%, whichever is the greater, over the range up to 1000 $\mu\mu$f, provided the dissipation factor of the unknown condenser is less than 0.1 (10%) and $\Delta D$ is less than 0.06 (6%). This accuracy can be maintained for greater dissipation factors by using first Equations (9) and then Equations (10). This error is double that of the standard condenser because in a substitution measurement two readings are taken and the errors of these two readings may be additive.

The adjustment of the standard condenser is such that the change in its error per turn is rarely greater than 0.2 $\mu\mu$f. Its worm correction or lack of linearity per turn is rarely greater than $\pm 0.1$ $\mu\mu$f. Hence the error in measuring 50 $\mu\mu$f is rarely greater than 0.3 $\mu\mu$f. For smaller capacitances the actual error will decrease with the capacitance. The lower limit of this error may be set at 1/5 of the smallest division or 0.04 $\mu\mu$f, or by the backlash of the worm drive, which is not greater than ½ of the smallest division or 0.1 $\mu\mu$f.

The standard condenser can be calibrated so as to be internally consistent to 0.1 $\mu\mu$f or 0.1%. This is the so-called worm correction.* Using the correction supplied by this calibration, capacitance can be measured to an accuracy of 0.2 $\mu\mu$f or 0.1%. A capacitance of 200 $\mu\mu$f is the smallest which can be measured to an accuracy of 0.1%.

The accuracy of the calculated dissipation factor is $0.00005 \times \frac{C'}{C_x}$ or 2%, whichever is the greater, provided the dissipation factor of the unknown condenser is less than 0.1 (10%) and $\Delta D$ is less than 0.06 (6%). This accuracy can be approximately maintained for greater dissipation factors by using first Equations (9) and then Equations (10). The error is always that of the change in DISSIPATION FACTOR readings. The minimum error indicated above can only be attained by using that part of the scale around zero. The power factor of a mica condenser, 0.05%, may thus be measured to an accuracy of 10%, if the ratio $\frac{C'}{C_x}$ can be made nearly unity.

*See the General Radio Catalog for data.

## C. SUBSTITUTION METHODS WITH EXTERNAL STANDARDS

An external Type 722 Precision Condenser can be used as a standard by connecting it across the UNKNOWN terminals and using the internal condenser merely as a balancing condenser. The METHOD switch is set at DIRECT. The use of such an external standard is of advantage only when this standard is provided with a worm correction or has a capacitance range especially suited to the work in hand.

Some of the advantages of the substitution method may be extended to capacitances greater than 1000 $\mu\mu$f whenever capacitance standards are available which are approximately equal to the unknown condenser. There are two different methods which use, respectively, the standard condenser in the bridge and an external standard variable air condenser.

### Method I—Internal Variable Standard

With the METHOD switch set at DIRECT, connect the fixed capacitance standard to the UNKNOWN CONDENSER terminals and balance the bridge for capacitance and dissipation factor. Substitute the unknown condenser for the standard condenser, using the same leads and rebalance the bridge. The capacitance and dissipation factor of the unknown are:

$$C_x = C_s + (C - C')M$$
$$D_x = D_s + (D - D') \qquad (11)$$

where the primes refer to the initial balance with the standard, $M$ is the setting of the MULTIPLIER switch, and $C_s$ and $D_s$ are the capacitance and dissipation factor of the fixed standard.

The accuracy of this comparison is determined by the difference in capacitance between standard and unknown. When $C - C'$ is less than 5 $\mu\mu$f, the errors in both capacitance and dissipation factor are almost entirely those of reading the two dials, as explained in Section B, 0.08 $\mu\mu$f for capacitance and 0.00005 for dissipation factor. The former corresponds to a fractional error of 0.08% at the smallest setting of the standard condenser, 100 $\mu\mu$f, which would ever be used.

By setting up tolerances for both the CAPACITANCE and DISSIPATION FACTOR dials, the bridge may be used as a limit bridge for rapidly checking lots of similar condensers.

A set of fixed standard condensers may be intercompared, provided there are enough duplicates so that each condenser may be matched by those smaller than itself. A convenient set of standards consists of pairs of condensers having values 1, 2, 5 per decade. Type 509 Standard Condensers are available in these ranges.* The two 1's are compared with the 2's; two 2's and a 1 with the 5's; two 5's with the 1's in the next decade and so on. Any condenser in the set may be taken as correct or their average may be used as a reference. Their dissipation factors may be determined by measuring the dissipation factor of the 0.001-$\mu$f standard by the substitution method of Section B. Intercomparisons of this nature are probably consistent to 0.04% in capacitance and to 0.00005 in dissipation factor.

*See the General Radio Catalog for data.

### Method II—External Variable Standard

With the METHOD switch set at DIRECT, connect the fixed capacitance standard to the UNKNOWN CONDENSER terminals together with an external standard variable air condenser and balance the bridge for capacitance and dissipation factor. The Type 722-D Precision Condenser is suitable for this use.* The standard condenser in the bridge is used merely as a balancing condenser. It is, however, equivalent to a three-decade condenser plus a variable air condenser, because of the possibility of using any one of the four ratio arms controlled by the CAPACITANCE MULTIPLIER. Substitute the unknown condenser for the fixed standard condenser, using the same leads, and rebalance the bridge, making the capacitance balance by means of the external standard variable air condenser. The capacitance and power factor of the unknown are:

$$C_x = C_s + (C' - C) \qquad (12)$$
$$D_x = D_s \frac{C_s}{C_x} + (D - D') \frac{C' + C_s}{C_x}$$

where $C'$ and $C$ refer to the initial and final capacitances of the external standard air condenser respectively, and $C_s$ and $D_s$ are the capacitance and dissipation factor of the fixed standard.

The accuracy of this comparison is determined by the difference in capacitance between standard and unknown. For capacitances of 1000 $\mu\mu$f or less the error is the same as stated in *Method I*. For larger capacitances the error in capacitance is less than occurs in Method I because the external standard air condenser, by means of which the capacitance difference is taken up, is a small fraction of the total capacitance. In general, the error is 2 $\mu\mu$f for an ordinary calibration of a 1000-$\mu\mu$f external air condenser and 0.2 $\mu\mu$f if it is supplied with a worm correction. The error is 0.00005 for dissipation factor as before.

A set of fixed standard condensers may be intercompared in the same manner as with Method I. These intercomparisons are probably consistent to 0.02% in capacitance and to 0.00005 in power factor.

*See the General Radio Catalog for data.

## PART 4—OTHER USES

### A. MEASUREMENT OF HIGH RESISTANCE

A high resistance may be measured by the substitution method described in Part 3, Section B. The unknown resistor is connected across the PARALLEL CONDENSER terminals by short bare leads. Its dissipation factor, series and parallel capacitance, and series and parallel resistance are given by Equations (10).

If the resistor has no reactive component so that

$$C_X = \infty \text{ and } C_{XP} = 0$$

its series resistance is the same as its parallel resistance as given in Equations (10).

There will still be a change of capacitance of the standard condenser given by

$$\Delta C = \frac{DC'\Delta D}{1 + D^2} \qquad (13)$$

where the dissipation factor reading $D$ must be increased by $D_0 = 0.042$ (4.2%).

A change of capacitance less than this value, zero, or of opposite sign implies that the resistor is inductive. Its series and parallel inductances are

$$L_X = -\frac{1}{\omega^2 C_X} \qquad (14)$$

$$L_{XP} = -\frac{1}{\omega^2 C_{XP}}$$

The largest resistance which can be detected, corresponding to a change in dissipation factor of 0.00002 is 80 $k\Omega$, with the standard condenser set at 100 $\mu\mu$f. The smallest measurable resistance corresponding to a change of dissipation factor of 0.56 (56%), the full range of the DISSIPATION FACTOR switch and dial, is 300 $k\Omega$, with the standard condenser set at 1000 $\mu\mu$f. The range in resistance varies inversely with the frequency.

### B. MEASUREMENT OF LARGE INDUCTANCE

A large inductance may be measured by the substitution method described in Part 3, Section B. The unknown inductor is connected across the PARALLEL CONDENSER terminals in the same manner as an unknown condenser. The change in capacitance $\Delta C$ will in general be negative, the final reading of the CAPACITANCE dial with the inductor connected being greater than its initial reading. Hence the balancing condenser must be less than 1100 $\mu\mu$f by at least the amount $\Delta C$.

The dissipation factor, series and parallel resistances, and equivalent series and parallel capacitances of the unknown inductor are given by Equations (6) and (8). Its series and parallel inductances can be calculated by Equations (14). For large values of dissipation factor it will be necessary to use first Equations (9) and then Equations (10). Its storage factor is the reciprocal of its dissipation factor.

$$Q_X = \frac{1}{D_X} \qquad (15)$$

The inductance range extends from 25 h to 1 Mh (1,000,000 h), corresponding to changes in capacitance of 1000 $\mu\mu$f and 0.02 $\mu\mu$f, respectively at 1000 cycles.

The range in inductance varies inversely with the square of the frequency. The resistance and reactance of a choke coil or parallel tuned circuit may be thus measured.

### C. PARTIAL SUBSTITUTION METHODS

The lower limit for the measurement of both resistance and inductance by the method described in Sections A and B may be made much smaller by using either of the two methods of Part 3, Section C.

For Method II, in which an external standard variable air condenser is used, Equations (6) and (8) to (10) hold unchanged. The lower limit of resistance is reduced to 300 Ω, with a total capacitance in circuit of 1 $\mu$f. Type 509 Standard Condensers may be used as external fixed standards.* The lower limit of inductance is still 25 h, corresponding to a change in capacitance of 1000 $\mu\mu$f, the range of the external standard.

For Method I, in which the bridge is balanced for capacitance by means of the internal standard air condenser, the procedure is modified to the extent that the fixed balancing capacitance is kept in circuit at all times. Equations (6) and (8) to (10) must be modified by transposing $C$

*See the General Radio Catalog for data.

and $C'$ wherever they appear, and multiplying them by $M$, the setting of the capacitance multiplier. The lower limit of resistance is reduced to 300 Ω, for a total capacitance in circuit of 1 μf. The lower limit of inductance is reduced to 25 mh for a change in capacitance of 1 μf. This limit varies inversely as the square of the frequency. Both Type 505 Condensers and Type 509 Standard Condensers may be used as the fixed balancing condenser.*

## D. SERIES SUBSTITUTION METHODS

Capacitances greater than 1 μf may be measured by connecting them in series with a fixed balancing condenser across the UNKNOWN CONDENSER terminals. The balancing condenser is first measured alone by the method of Part 3, Section A. The unknown condenser is then connected in series between the balancing condenser and the ground terminal. Its series capacitance, dissipation factor and series resistance are

$$C_x = \frac{C'C}{\Delta C}$$

$$D_x = \Delta D \frac{C'}{\Delta C} \qquad (16)$$

$$R_x = \frac{\Delta D}{\omega C}$$

The largest capacitance which can be detected is 50 $m$f (0.05 f) for a fixed capacitance of 1 μf and a change in capacitance of the standard air condenser of 0.02 μμf. When the dissipation factor reading with the unknown condenser connected is greater than 0.1 (10%), the fixed capacitances across the ratio arms $A$ and $B$ introduce sufficient errors so that Equations (17) must be used.

$$C_x = \frac{MCC'(1 + D_o^2)}{\Delta C(1 + D_o^2) + D_o(DC' - D'C)}$$

$$D_x = \frac{DC' - D'C}{\Delta C(1 + D_o^2) + D_o(DC' - D'C)} \qquad (17)$$

$$R_x = \frac{DC' - D'C}{\omega MCC'(1 + D_o^2)}$$

*See the General Radio Catalog for data.

where $D_o$ is the dissipation factor corresponding to the fixed capacitances across the ratio arms and has the value 0.034 (3.4%).

Small inductances may be measured by this method. As with condensers, the inductor is connected in the ground lead of the fixed balancing condenser. Its series inductance, dissipation factor, series resistance and storage factor are

$$L_x = -\frac{\Delta C}{\omega^2 CC'}$$

$$D_x = \Delta D \frac{C'}{\Delta C} \qquad (18)$$

$$R_x = \frac{\Delta D}{\omega C}$$

$$Q_x = \frac{1}{D_x}$$

For large dissipation factors Equations (17) must be used together with Equations (14) and (15). The smallest inductance which can be detected is 0.5 μh for the same limiting conditions of balance as for capacitance. This limit varies inversely as the square of the frequency.

The ranges for both capacitance and inductance may be extended by connecting a standard variable air condenser in parallel with the fixed balancing condenser as indicated in Part 3, Section C, Method II. Equations (16), (17) and (18) hold except that $C$ and $C'$ are transposed. The limits for capacitance and inductance are 1 f and 0.025 μh, based on a sensitivity of capacitance balance of 1 part per million.

## E. SERIES RESISTANCE METHOD

The series resistance of a condenser having a capacitance of 1000 μμf or less may be measured by modifying the substitution method of Part 3, Section B, as shown in Figure 3. The resistance balance is made by means of a decade resistor, such as a Type 602 Decade Resistance Box,* connected in the ground lead of the balancing condenser. If the initial resistance balance is made by means of the DISSIPATION FACTOR dial, leaving the decade resistor set at zero when the unknown condenser is not connected, the change in resistance is the setting of this decade resistor for the second balance. The

series capacitance and series resistance of the unknown condenser are

$$C_X = \Delta C$$
$$R_X = \left(\frac{C'}{\Delta C}\right)^2 \Delta R \qquad (19)$$

Since the change in resistance corresponding to a change in power factor of 0.00002 is greater than 0.1Ω, smaller changes in power factor may be made by means of the added decade resistor than by the DISSIPATION FACTOR dial. It is difficult, however, to make the dissipation factor balance on the bridge to better than 0.000001 (one millionth).

An external standard variable air condenser may be used by connecting it across the UNKNOWN CONDENSER terminals with the decade resistor in series in the ground lead. The unknown condenser is then connected in parallel with the standard condenser only. The bridge is balanced for resistance by means of the DISSIPATION FACTOR dial with the decade resistor set at zero. The unknown condenser is then disconnected and the change in resistance is the setting of the decade resistor for the second balance. Equations (19) hold for this method, C′ being the capacitance of the external standard condenser when the unknown condenser is not connected.

## F. PARALLEL RESISTANCE METHOD

The parallel capacitance and resistance of condensers within the range 100 μμf to 1 μf may be measured directly by making the resistance balance on a decade resistor connected across the PARALLEL CONDENSER terminals in parallel with the internal standard condenser as shown in Figure 4. The DISSIPATION FACTOR switch and dial must be set at zero. The resistance range is determined by that of the decade resistor.

$$C_{XP} = MC$$
$$R_{XP} = \frac{R}{M} \qquad (20)$$

where the capacitance reading C must be increased by the parallel capacitance of the decade resistor. This capacitance varies with the number of decades and the settings of these decades between 10 and 40 μμf.* For a maximum setting of the decade resistor of 100 kΩ, the lower limits of dissipation factor are 16 for a capacitance of 100 μμf and 1.6 for 1 μf.

The parallel capacitance and resistance limits may be extended by the substitution method shown in Figure 5. A balancing condenser and resistor in parallel are connected across the UNKNOWN CONDENSER terminals and a decade resistor of 100 kΩ maximum is placed across the PARALLEL CONDENSER terminals. Using a balancing capacitance of 100 $M$ μμf and a balancing resistance of $\frac{100}{M}$ kΩ, the bridge will balance with the CAPACITANCE dial at about 100 μμf and the decade resistor set at about 100 kΩ. The unknown condenser

*D. B. Sinclair, "Radio Frequency Characteristics of Decade Resistors", General Radio *Experimenter*, Vol. XV, No. 6, Dec. 1940.

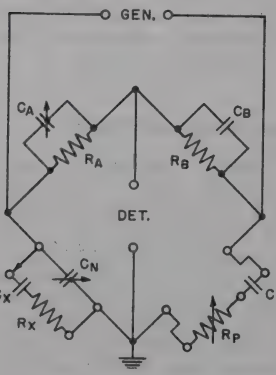



Figure 3. Substitution Series-Resistance Method.

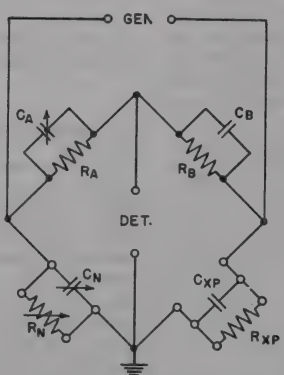



Figure 4. Parallel-Resistance Method.

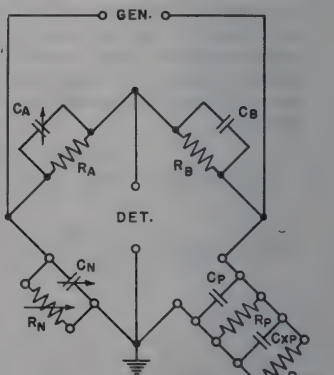



Figure 5. Substitution Parallel-Resistance Method.

is then connected across the UNKNOWN CONDENSER terminals and the bridge rebalanced by increasing the setting of the standard condenser and decreasing that of the decade resistor. The parallel capacitance and resistance of the unknown condenser are

$$C_{XP} = M\Delta C \qquad R_{XP} = \frac{RR'}{M\Delta R} \qquad (21)$$

where the change in capacitance $\Delta C$ must include the change in parallel capacitance of the decade resistor.* The smallest setting $M$ of the MULTIPLIER switch which allows a capacitance balance should be used. The largest resistance which can be detected corresponding to a change in resistance of 1 part in a million is 100 kmΩ with the MULTIPLIER switch set at 1.

High resistances, large inductances and parallel tuned circuits may be measured in a similar manner. An inductance will cause the setting of the standard condenser to decrease when it is connected across the UNKNOWN CONDENSER terminals. Either a larger balancing condenser should be used or the inductor should be connected across the PARALLEL CONDENSER terminals. For the latter case the fixed and decade resistors should be transposed. Equations (21) still hold except that usually the MULTIPLIER switch is set at 1. Inductance is calculated from Equation (14).

## G. VOLTAGE LIMITS

The junctions of the ratio arms and of the capacitance arms, the latter being grounded, are brought out to the terminals marked DETECTOR as shown in Figure 6. A shielded transformer is connected across the ratio arms and its low-voltage winding connected to the terminals marked GENERATOR. This connection of the power supply produces maximum sensitivity of balance for the measurement of small capacitances.

The voltage which may be applied to the GENERATOR terminals is limited by the power dissipation of the ratio arms. The fixed arm $A$ is 20 kΩ and will dissipate 1 watt. The characteristics of the $B$ arm, which is controlled by the MULTIPLIER switch, and the maximum voltages which may be applied across the ratio arms and across the GENERATOR terminals are given in Table II. It is safe to use any generator with a maximum output of 2 watts. The shielded transformer steps up the voltage from GENERATOR terminals to bridge by a factor of about 3.5.

TABLE II

| Multiplier | 1 | 10 | 100 | 1000 |
|---|---|---|---|---|
| B kilohms | 20 | 2 | .2 | .02 |
| B watts | 1 | .5 | .5 | .5 |
| B volts | 150 | 30 | 10 | 3 |
| B ma | 7.5 | 15 | 50 | 150 |
| Bridge volts | 300 | 180 | 155 | 153 |
| GENERATOR volts | 85 | 50 | 45 | 44 |
| DETECTOR volts | 700 | 240 | 80 | 24 |

A much higher voltage can be applied across the UNKNOWN CONDENSER terminals by connecting the power supply to the DETECTOR terminals. The limit is determined either by the maximum voltage of the standard condenser, 700 volts, or by the maximum current of the $B$ arm. The last line of Table II gives these limits.

The increased voltage which can be used across the DETECTOR terminals will tend to offset the lowered sensitivity of the bridge for this connection. No power will be lost in the transformer and usually less in the ratio arms. This will shorten the time needed to attain temperature equilibrium of the bridge after the power is applied. Although the errors caused by these temperature changes are less than the limits given in Table I, they are sometimes annoying in substitution methods because they shift the initial balance.

## H. OTHER FREQUENCIES

The bridge will operate at all audio frequencies from 50 cycles to 10 kilocycles. The capacitance range is unaffected by frequency. The dissipation factor range is directly proportional to frequency. It is, therefore, 0.03 (3%) at 50 cycles and 5.6 (560%) at 10 kilocycles. The smallest detectable dissipation factor is similarly affected, being 0.0001% at 50 cycles and 0.02% at 10 kilocycles.

A dissipation factor of 0.000001 (one millionth) is essentially the limit of sensitivity of the bridge. It requires complete freedom from extraneous voltages both in the amplifier and in the bridge itself. When power is taken from the local power supply at 60, 50 or 42 cycles, it is very difficult to prevent the electric and magnetic fields from the wiring and from mo-

*D. B. Sinclair, "Radio Frequency Characteristics of Decade Resistors", General Radio *Experimenter*, Vol. XV, No. 6, Dec. 1940.

## RESISTORS

R-1= 20Ω 510-340
R-2= 200Ω 500-30E
R-3= 2KΩ 510-341
R-4= 20KΩ 602-305 (2 in series)
R-5= 20KΩ 602-305 (2 in series)

## CONDENSERS

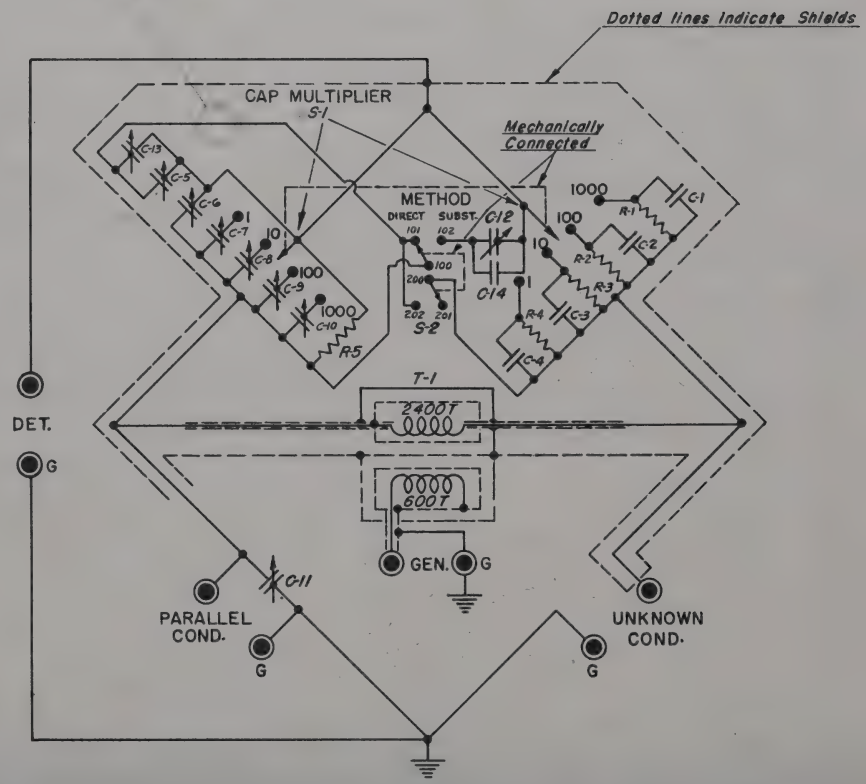
C-1= 0.270μf Type 505
C-2= 0.0269μf Type 505
C-3= 0.00263μf Type 505
C-4= 0.000200μf Type 505
C-5= 500μμf 539-T (reverse rotor)
C-6= 50μμf } Hammarland APC Type C G.R.Co. #139-1203C
C-7= 50μμf
C-8= 50μμf
C-9= 50μμf
C-10= 50μμf
C-11= 1100μμf 722-402
C-12= 50μμf 139-1203C
C-13= 380-400
C-14= 0.0001μf Dubilier Type 5W

## SWITCHES

S-1= 716-33
S-2= 139-1430-1

## TRANSFORMER

T-1= 578-401




WIRING DIAGRAM OF 716-B CAPACITANCE BRIDGE

Figure 6.

tors from inducing considerable voltages in the bridge. Exposed leads to the balancing and unknown condensers pick up voltages from the electric field, while the shielded transformer is affected by the magnetic field. The magnetic field usually fluctuates with wide limits so that even substitution methods are affected. Measurements under these conditions are rarely reliable to better than 0.000010 (10 millionths) for dissipation factor. It is often advisable to use a frequency differing sufficiently from the power supply frequency so that these extraneous voltages can be removed by suitable filter circuits. Even a slight difference in frequency which produces a slow beat between the frequencies is sufficient, because then in order to balance the bridge it is only necessary to reduce to zero the amplitude of this beat.

## I. MEASUREMENT OF INSULATING MATERIALS

The dielectric constant and dissipation factor of a solid dielectric are obtained by applying suitable electrodes to the material and measuring its capacitance and dissipation factor by one of the methods described in Parts 3 and 4. Satisfactory results are obtained when the material is in the form of thin slabs. Electrodes may be squares or circles cut from lead foil and fixed to the slab by a very thin coat of petrolatum. The dielectric constant of the material is

$$K = \frac{C_x}{C_o} = \frac{1.130\, d\, C_x}{A} \ (\mu\mu f,\ cm) \qquad (22)$$

$$= \frac{4.45\, d\, C_x}{A} \ (\mu\mu f,\ inches)$$

where $C_o$ is the air capacitance between the two electrodes. It is given by

$$C_o = 0.0885\, \frac{A}{d}\ \mu\mu f \ (centimeters) \qquad (23)$$

$$= 0.2248\, \frac{A}{d}\ \mu\mu f \ (inches)$$

where $A$ is the area of the electrodes and $d$ the thickness of the slab.

Fringing at the edges, which varies with the type of electrodes and the value of the dielectric constant, may produce errors in the calculation of dielectric constant as great as 10%. Formulae are available* for calculating the magnitude of this fringing, which will reduce this error to less than 3% in most cases. Frequently the error in the measurement of thickness is greater than this.

A simple approximation to the more accurate formulae is to add half the thickness to the diameter for equal circular electrodes and the whole thickness to the diameter of the smaller circular electrode if the other is much larger. For rectangular electrodes each side is increased by the amount given above.

Mercury confined by metal rings makes satisfactory electrodes when the rings are carefully centered. The lower electrode may also be obtained by floating the slab in a tray of mercury. The capacitance of the upper electrode to ground may amount to several $\mu\mu f$. It can be measured approximately by the substitution method of Part 3, Section B.

Dissipation factor measurements are unaffected by fringing except when the dissipation factor of the material varies with voltage gradient. Even when the ground capacitance is considerable, the error in dissipation factor is not serious unless the measured dissipation factor is small.

## J. MEASUREMENT OF DIRECT CAPACITANCE

The direct capacitance† between two terminals may be separated from the capacitance of these terminals to a surrounding shield by connecting this shield to the junction of the ratio arms and balancing the bridge by the direct reading method of Part 3, Section A. The bridge reads too high in power factor because one of the terminal capacitances is connected across ratio arm *B*. Even the substitution method of Part 3, Section B, does not give the correct value for power factor because the terminal capacitances placed across ratio arm *A* are not the same for the two balances of the bridge.

*A. H. Scott: "Determination of the Edge Correction in the Measurement of Dielectric Constant," *Proc. ASTM*, Vol. 37, Part II, 1937, pp. 655-660.

†R. F. Field, "Direct Capacitance and Its Measurement," General Radio *Experimenter*, Vol. VIII, No. 6, November, 1933.

These terminal capacitances placed across a ratio arm affect slightly the resistance of that arm, because of their losses. Hence in the substitution method an error of perhaps 0.1 $\mu\mu$f may occur in the capacitance measurement. While such an error is generally negligible, it is large enough to prevent the measurement of such small direct capacitances as the grid-to-plate capacitance of a screen-grid vacuum tube. The error is always in the direction to give too small a capacitance. Its presence is frequently detected by the fact that the calculated capacitance is negative. This error can be greatly reduced by disconnecting the condenser on the ground side. This makes the terminal capacitance placed across the $A$ arm for the two balances differ only by the direct capacitance being measured.

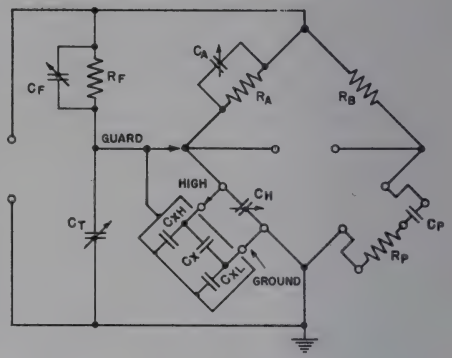



Figure 7. Guard Circuit for Three-Terminal Condenser.

### Guard Circuit

The errors produced by connecting the shield or third terminal to the junction of the ratio arms may be eliminated by connecting this terminal to a guard circuit placed across the DETECTOR terminals as shown in Figure 7. The units of the guard circuit $FT$ are best made of the same size as those forming the bridge arms $AN$.

The bridge is balanced initially with the connections as shown. The junction of the guard arms $FT$ is then connected to the junction of the bridge arms $AN$ and the bridge rebalanced by means of the condensers $C_T$ and $C_F$. Successive bridge and guard balances must be made until both are simultaneously balanced. It will usually be impossible to balance the guard circuit for dissipation factor without having first added a resistance $R_P$ in series with the balancing condenser $C_P$. This is because of the relatively large losses in the terminal capacitances $C_{XH}$ and $C_{XL}$ and in the ground capacitances of the guard arm $F$. Instead of adding a resistance in the $P$-arm, it may be more convenient to place a condenser across the $B$-arm. The losses in the guard circuit can also be compensated by introducing a suitable inductance in series with the resistance $R_F$. This is equivalent to a negative capacitance placed across $R_F$. Its magnitude in relation to the capacitance $C_F$ may be calculated from the expression $L_F = R_F^2 C_F$.

The unknown condenser is then connected on its high side and bridge and guard circuits rebalanced as before. The guard circuit balance will be different because the terminal capacitance placed across $C_T$ is changed. More successive balances will also be required because bridge and guard circuits are now connected by the terminal capacitance $C_{XH}$. The direct capacitance $C_X$ and its dissipation factor are given by Equation (6).

## K. GUARD ELECTRODES

The use of the guard circuit described in Section J makes it possible to eliminate all of the errors discussed in Section I in the measurement of insulating materials. The slab of dielectric is placed in a shielded compartment insulated from the ground and having the electrodes connected as in Figure 8. The measuring electrodes are circular and the guard electrode annular. When the slab has a sufficiently plane surface, these electrodes may be spring-pressed to it, otherwise lead foil electrodes are used and contact made to them. Mercury electrodes may also be used, confined in concentric rings. In this case the top of the shielded compartment is omitted and the high measuring electrode is shielded only by the guard ring.

When the power is supplied to the bridge at the DETECTOR terminals, the high measureing and guard electrodes are at the same potential and the electric field through the slab is uniform all over the central electrode. This eliminates all effects from non-uniform voltage gradients.

When the high lead is completely shielded, it may be opened anywhere along its length for the two bridge balances. The small capacitance across the switch can be eliminated by connecting the high electrode to guard for the initial

balance. This places the capacitance being measured in the guard circuit and necessitates a large change in the setting of condenser $C_T$.

Such a cell as that shown in Figure 8 could be used for measuring the dielectric constant and power factor of a liquid provided it were made tight. It is usual, however, to make the electrodes cylindrical and place guard cylinders at both ends. This type of construction usually provides a greater capacitance for a given amount of liquid.

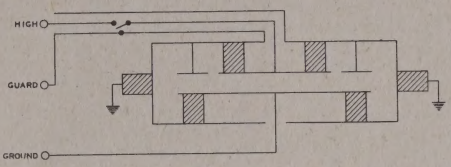



Figure 8. Guard Electrodes and Connections.

# PART 5—CONSTRUCTION

## A. ELECTRICAL CIRCUIT

The wiring diagram of the Type 716-B Capacitance Bridge is shown in Figure 6. All features of the design are directed toward making it direct reading in capacitance and power factor over the entire capacitance range to the greatest possible accuracy. The most important features of the design are the complete shielding of both ratio arms and transformer and the compensation for capacitance of the variable ratio arms so that the storage factor $R_B\omega C_B$ is constant for all settings of the MULTIPLIER switch.

## B. ADJUSTMENTS

### Standard Condenser

The standard condenser has been adjusted to be direct reading in capacitance from 100 to 1100 $\mu\mu$f to an accuracy of 1 $\mu\mu$f. The pair of plates at each end of the stator stack control the internal consistency of this calibration and are adjusted before the condenser is mounted in the bridge. The two screws in the frame change the zero capacitance of the condenser and are adjusted after all other adjustments have been made to make the bridge read correctly in capacitance. This compensates for the capacitances of the UNKNOWN CONDENSER and PARALLEL CONDENSER terminals and for the leakage impedances of the shielded transformer.

The dissipation factor of this condenser varies from 0.004% at 1000 $\mu\mu$f to 0.04% at 100 $\mu\mu$f, corresponding to a figure of merit DC of 0.04 $\mu\mu$f.

### Dissipation Factor Condensers

The dissipation factor scale of the air condenser corresponds exactly to capacitance differences measured from an arbitrary zero chosen near its minimum capacitance setting, such that the dissipation factor limits of $-0.15\%$ and $+6\%$ appear.

The decade condensers are moulded mica units similar to Type 380 Decade Condenser Units, so chosen that each step is 398 $\mu\mu$f, giving a dissipation factor of 0.05 (5%) for each step with an accuracy of $\pm 1\%$.

The decade and air condensers are connected across either the *A* or *B* arm of the bridge by means of the METHOD switch, across the *A* arm in the DIRECT position, across the *B* arm in the SUBSTitution position.

### Shielded Transformer

The shields around both windings are connected to the winding to eliminate all terminal capacitances. A third shield between the two winding shields is connected to the transformer case and to the main insulated shield of the bridge, which in turn is connected to the junction of the ratio arms. The capacitance between these shields and the bridge winding shield is placed across the *A* ratio arm and amounts to about 110 $\mu\mu$f. It will change appreciably with temperature.

The direct impedances between the generator winding and the other two shields are all kept greater than 10 kMΩ by the completeness of the shielding and impregnation of the windings. The connections between GENERATOR terminals and bridge are so made that the small residual impedances tend to neutralize the varia-

tion of dissipation factor of the standard condenser with setting. Slight changes in these leakage impedances will occur with temperature and humidity.

### Ratio Arms

The ratio arms are all mounted on a double arm switch, which controls both the choice of ratio arms and the compensating condensers. The switch is made of yellow low-loss bakelite, so that the parallel resistance representing its losses will not appreciably shunt the 20 kΩ ratio arms.

### Compensating Condensers

With the DISSIPATION FACTOR switch and dial set at zero and the METHOD switch set at DIRECT, the total capacitance across the *A* arm is 270 $\mu\mu$f ± 5%. This is made up roughly of 100 $\mu\mu$f from the transformer, 60 $\mu\mu$f from the dissipation factor condensers, 60 $\mu\mu$f from the wiring of all the condensers in the *A* arm, and 25 $\mu\mu$f each from the ZERO ADJUSTMENT condenser and whichever of the variable air condensers is in circuit, each being set at about half scale. This capacitance of 270 $\mu\mu$f is balanced in the *B* arm by four mica condensers, one for each of the four ratio arms, with capacitances of 200 $\mu\mu$f, 2.63, 26.9 and 270 m$\mu$f. The wiring capacitance of this arm is 70 $\mu\mu$f. When the METHOD switch is set at SUBSTitution, the zero capacitance of the dissipation factor condensers is added across the *B* arm. This transferred capacitance is balanced in the *A* arm by a 100 $\mu\mu$f mica condenser and a variable air condenser set at approximately 20 $\mu\mu$f. The total capacitance across the *A* arm is thus increased to 330 $\mu\mu$f.

The four air condensers are adjusted by connecting in turn across the UNKNOWN CONDENSER terminals four mica condensers of known capacitance and dissipation factor, one for the maximum capacitance setting of each MULTIPLIER position. With the DISSIPATION FACTOR dial set at the known dissipation factor the bridge is balanced for dissipation factor by the compensating air condensers. The fifth air condenser is adjusted in a similar manner with the METHOD switch set at SUBSTitution, the CAPACITANCE MULTIPLIER set at 1 and the DISSIPATION FACTOR dial set at minus the known dissipation factor.

With these approximate adjustments a complete set of air and mica standard condensers are measured, units of 1, 2, 5 in each decade from 100 $\mu\mu$f to 1 $\mu$f. Slight readjustments of the five air condensers and of the zero setting of the standard precision condenser are then made to obtain the most accurate adjustments.

Changes in the inter-shield capacitances of the shielded transformer due to temperature will affect equally the dissipation factor readings on all four MULTIPLIER settings. The accuracy of the dissipation factor readings of the bridge as affected by this capacitance may be checked at any time by measuring any condenser of known dissipation factor. If none is available, the dissipation factor of any condenser having a capacitance between 100 and 1000 $\mu\mu$f can be measured by the substitution method of Part 3, Section B, and then used as a standard.

The adjustment of the compensating air condensers for the other MULTIPLIER settings can be checked only if a complete set of standards is available. Both the bridge and the set of standards can be checked and intercompared in one hour by Method 1 of Part 3, Section C.

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